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RESEARCH MEMORANDUM

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DETERMINATION OF GAS-TO-BLADE CONVECTION HEAT-TRANSFER COEFFICIENTS ON A FORCED-CONVECTION, WATER-COOLED SINGLE-STAGE ALUMINUM TURBINE

By John C. Freche and Eugene F. Schum

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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DETERMINATION OF GAS-TO-BLADE CONVECTION HEAT-TRANSFER COEFFICIENTS ON A FORCED-CONVECTION, WATER-COOLED, SINGLE-STAGE ALUMINUM TURBINE

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SUMMARY

Gas-to-blade convection heat-transfer coefficients were obtained on a forced-convection, water-cooled, single-stage aluminum turbine over a range of gas-flow Reynolds numbers and inlet-gas temperatures at several computed gas-flow inlet angles. Radiation to the blades was negligible. The convection coefficients were obtained for the nominal-design gas-flow inlet angle of 37° over a range of gas-flow Reynolds numbers from 30,000 to 110,000 and for a limited Reynolds number range at computed inlet angles of 25°, 43°, and 49°. The range of inlet-gas temperatures covered was from 250° to 1250° F.

Gas-to-blade convection coefficients were correlated at each inlet angle by the general relation for forced-convection heat transfer that expresses Nusselt number as a function of Reynolds and Prandtl numbers. The root-mean-square deviation of the data from the correlation curve obtained at the nominal-design gas-flow inlet angle of 37° was $5\frac{1}{2}$ percent.

Individual gas-to-blade convection heat-transfer correlation curves resulted from turbine operation at several gas-flow inlet angles. As the computed inlet angle was increased from 25° to 43°, the gas-to-blade heat-transfer rate increased an average of 34 percent for the range of Reynolds numbers considered.

The correlation curve for the data obtained at the 37° gas-flow inlet angle was compared with those from static-cascade results for impulse blades and showed agreement within 9 percent. From the agreement between the experimental and computed gas-to-blade heat-transfer results, theory may be used to compute the gas-to-blade convection heat-transfer correlation for this turbine configuration at the design gas-flow inlet angle.

INTRODUCTION

Heat-transfer investigations with cooled turbine blades in static cascades have been conducted by NACA (reference 1), British (reference 2), and German investigators (references 3 and 4). The gas-to-blade heat-transfer data from these investigations have been correlated by the general relation for forced-convection heat transfer that expresses Nusselt number as a function of Reynolds and Prandtl numbers. A compilation of the results of the NACA, British, and German investigations are presented in reference 5.

Because gas-flow conditions in turbines cannot be entirely duplicated in a static cascade, average gas-to-blade convection heat-transfer coefficients were determined on a forced-convection, water-cooled, aluminum turbine and are described in reference 6. Gas-to-blade as well as blade-to-coolant convection coefficients and coolant pumping power were also obtained with the aluminum turbine. The gas-to-blade heat-transfer data of this investigation (reference 6) cover a small range of gas-flow Reynolds numbers and inlet-gas temperature, and are confined to one gas-flow inlet angle.

In order to continue the quantitative evaluation of laws governing the heat transfer in and around cooled turbine blades so that the designer can predict blade temperatures, an investigation of gas-to-blade and blade-to-coolant heat transfer was conducted on a forced-convection, water-cooled aluminum turbine at the NACA Lewis laboratory. Gas-to-blade convection heat-transfer coefficients, which are presented herein, were obtained for the nominal design gas-flow inlet angle of 37° over an extended range of gas-flow Reynolds numbers from 30,000 to 110,000 and for a limited Reynolds number range at computed inlet angles of 25°, 43°, and 49°. The range of inlet-gas temperatures covered in this investigation was from 250° to 1250° F. The correlation curve for the data obtained at the 37° gas-flow inlet angle is compared with those from static-cascade results for impulse blades and with a gas-to-blade heat-transfer correlation curve computed by means of boundary-layer theory.

APPARATUS

The NACA forced-convection, water-cooled, single-stage aluminum turbine operated in this investigation is fully described in reference 6. Turbine, turbine installation, hot-gas system, and instrumentation are the same as those described in reference 6. A cutaway section of the turbine blade and a cross section of the turbine installation are shown in figure 1. The turbine has 50 impulse blades; these blades are of constant cross section with a chord of 0.744 inch, span of 1.15 inches, and have no twist. The path of the coolant through the blade and the blade-construction details are shown in figure 1(a). The path of the coolant through the entire turbine and the planes of instrumentation through the rig are shown in figure 1(b).

Accuracy. - The accuracy of the measurements is estimated to be within the following limits:

Blade temperature, °F	±2
Gas temperature, °F	±10
Pressures, in. Hg	±0.10
Coolant-flow rate, percent	±1

PROCEDURE

The turbine was operated to obtain gas-to-blade heat-transfer coefficients over a wide range of gas-flow Reynolds numbers at the nominal-design gas-flow inlet angle of 37°. Over 100 runs were made to establish the gas-to-blade heat-transfer correlation curve at this inlet angle. Some of these data are reported in reference 6. Gas-to-blade heat-transfer coefficients were also obtained over a limited Reynolds number range at three additional calculated inlet angles, 25°, 43°, and 49°. Probable separation of the gas flow around the blade at a 49° inlet angle affected the gas-to-blade heat transfer and resulted in establishing this angle as the upper limit of the range. Furthermore, mechanical limitations of the turbine installation prevented operation over a greater range of inlet angles. The range of turbine operating conditions covered is given in table I. In order to insure longer turbine life, operation at low-stress levels was maintaned for the off-design inlet-angle runs and prompted the choice of low inlet-gas temperatures for these runs. Turbine operation at a particular gas-flow inlet angle was achieved by setting the inlet-gas temperature, pressure ratio, and turbine speed according to previously calculated values. The turbine speed was adjusted by means of a water brake to the proper calculated value in order to obtain a desired inlet angle for any condition of pressure ratio and inlet-gas temperature.

The nozzle-box survey described in reference 6 provided a relation between the survey readings at the stator outlet and readings from the stationary instrumentation at the stator inlet and throat. The relation was applied to all operating points of this investigation.

SYMBOLS

The following symbols are used in this report:

A	flow area normal to gas stream, (sq ft)
c_p	specific heat of gas at constant pressure, Btu/(lb)(°F)
D	characteristic dimension, $\frac{\text{blade perimeter}}{\pi}$, (ft)
g	acceleration due to gravity, (ft/sec^2), or ratio of absolute to gravitational unit of mass, (lb/slug)
H	gas-to-blade convection heat-transfer coefficient, Btu/(°F)(sq ft)(sec)
J	mechanical equivalent of heat, 778.3 (ft-lb)/Btu
k	thermal conductivity of gas (evaluated on the basis of blade temperature), Btu/(°F)(ft)(sec)
Nu	Nusselt number, HD/k
p	absolute static pressure of gas, (lb/sq ft)
p'	absolute total pressure of gas, (lb/sq ft)
Pr	Prandtl number of gas (evaluated on the basis of blade temperature), $c_p \mu g/k$
Q	heat flow per unit time, Btu/(sec)
R	specific gas constant, (ft-lb/(lb)(°F))
Re	Reynolds number
Re_i	gas flow Reynolds number at rotor inlet, $\frac{wDT_{g,i}}{A_i \mu g T_B}$ or $\frac{p_i W_i D}{RT_B \mu g}$
Re_{av}	average gas flow Reynolds number around blade, $\frac{p_{av} W_{av} D}{RT_B \mu g}$
S	surface area, (sq ft)

T	static temperature, $^{\circ}R$
T'	total temperature, $^{\circ}R$
V	absolute velocity of gas, (ft/sec)
W	relative gas velocity, (ft/sec)
w	weight flow of gas, (lb/sec)
β	gas-flow inlet angle measured from plane perpendicular to axis of rotation (fig. 3), (deg)
γ	ratio of specific heats
μ	absolute viscosity of gas (evaluated on basis of blade temperature), slugs/(ft)(sec)

Subscripts:

av	average along blade periphery
B	blade
e	effective
g	gas
h	disk rim (exposed peripheral section between blades)
i	rotor inlet
m	midspan
o	stator outlet
T	blade tip

METHODS OF CALCULATION

Experimental blade-surface coefficients. - The gas-to-blade convection coefficients were determined exactly as described in reference 6. These so-called convection coefficients might more accurately be termed "over-all coefficients" because the effect of radiation from the gas and the uncooled stator blades is included in the heat absorbed by the coolant. Calculations indicate, however, that the radiation effect for these runs is negligible so that the heat-transfer coefficient is considered to be a convection coefficient. The coefficient obtained is an average for the blade, the blade tip, and the disk rim between the blades because the instrumentation does not permit a separate evaluation of the amount of heat absorbed by the coolant through each of these sections exposed to the gas stream. An integrated average of the thermocouple readings based on the surface area about the blade midsection provided the average blade temperature. Single thermocouples at the blade tip and the blade base provided the temperatures used for the blade tip and the disk rim. The expression used to determine the average gas-to-blade convection coefficient is

$$H = \frac{Q}{\left[S_B(T_{g,e}-T_{B,m}) + S_T(T_{g,e}-T_T) + S_h(T_{g,e}-T_h)\right]} \tag{1}$$

The heat flow Q was determined from the heat rejected to the coolant. If the previously tabulated inaccuracies of measurement used in calculating the convection coefficients are assumed to be accumulative, a maximum error of 15 percent results. It should be stressed, however, that the accumulative error always exceeds the average error.

Correlation of the gas-to-blade coefficients was achieved in the same manner as in reference 6 on the basis of the general equation for forced-convection heat transfer:

$$Nu = f(Re,Pr) \tag{2}$$

Fluid properties of the gas were based on the average blade-wall temperature. A better correlation can be achieved in this way than by using the film temperature, as indicated in reference 5. The density was based on the rotor-inlet static pressure and the average blade-wall temperature; the weight flow per unit area was determined at the rotor-blade inlet and varied with gas-flow inlet angle. The characteristic dimension D in the Nusselt and Reynolds numbers was considered to be the blade perimeter divided by π.

The gas-flow inlet angles were determined from velocity diagrams. In order to obtain the velocity diagram for a particular turbine-inlet temperature, inlet pressure, and pressure ratio, the absolute stator-outlet velocity was calculated from the following equation:

$$V_o = \sqrt{2gJ} \sqrt{c_p T'_{g,o}\left[1 - \left(\frac{p_o}{p'_o}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{3}$$

From the values given in table I, it can be seen that the experimental pressure ratio is below the critical value for the range of operating conditions covered in this investigation. The gas was assumed to leave the stator at the stator-blade outlet angle of 22°. The maximum inaccuracy of measurements, as previously indicated, was assumed to apply to the readings involved in computing a gas-flow inlet angle for several representative runs. A maximum deviation from the originally computed angle of 1° and a minimum deviation of $1/4^{\circ}$ resulted.

Theoretical blade-surface convection coefficients. - The theoretical gas-to-blade heat-transfer correlation was calculated for the nominal-design gas-flow inlet angle. An unpublished stream-filament theory recently derived for compressible flow around an impulse blade was employed to obtain a velocity distribution around the aluminum turbine blade. The velocity distribution so obtained was used in the calculation to obtain the convection gas-to-blade coefficients. Some inaccuracies may result in the velocity distribution around the blade periphery when this stream-filament theory is employed. These inaccuracies are therefore reflected in the calculations for gas-to-blade convection heat-transfer coefficients. The gas-to-blade heat-transfer correlation curves were not compared for off-design inlet angles because the stream-filament theory is insensitive to variation in inlet angle. The method used for calculating the gas-to-blade convection coefficients and obtaining the theoretical gas-to-blade heat-transfer correlation is described in reference 7 (appendix B).

The theoretical correlation utilizes the conditions of average blade temperature, gas pressure, and velocity around the blade. In order to provide a comparison between the theoretical and the experimental correlations, both correlations had to be reduced to a common basis. From the definitions of inlet and average Reynolds numbers, the relation between them was found to be

$$Re_{av} = Re_i \left(\frac{p_{av}W_{av}}{p_iW_i}\right) \tag{4}$$

RESULTS AND DISCUSSION

Design inlet-angle runs. - The data of all the runs made at a 37° gas-flow inlet angle are plotted in figure 2. The least-square curve through these data was correlated according to the equation

$$\frac{Nu}{Pr^{1/3}} = 0.117 \ Re_i^{0.70}$$

The root-mean-square deviation of the data from the curve represented by this equation is $5\frac{1}{2}$ percent. These data were obtained over a range of gas stream-to-blade temperature ratios from 1.18 to 2.24. The scatter of the data was such that no definite trend in variation of the slope could be observed for various gas stream-to-blade temperature ratios for the data obtained.

Off-design inlet-angle runs. - The effect of gas-flow inlet angle on the average gas-to-blade convection coefficient is shown in figure 3. The data obtained at the computed inlet angles of 25° and 43° are plotted in figure 3(a). The least-square curve through the data obtained at the inlet angle of 37° is also shown in figure 3(a). The slopes of these curves are identical. For the range of Reynolds numbers covered, as the inlet angle increases the Nusselt number increases because the heat-transfer coefficient increases. The average increase in Nusselt number is 34 percent for a corresponding increase in inlet gas-flow angle from 25° to 43°.

The static-cascade results for various gas-flow inlet angles (reference 3) indicate that a minimum heat-transfer rate occurs at a specific gas-flow inlet angle for a constant Reynolds number. The Nusselt number increases as the inlet angle is decreased or increased from this specific value. As previously indicated, mechanical limitations prevented operation of the aluminum turbine over a greater range of gas-flow inlet angles than those considered so that the value of the inlet angle for minimum heat transfer for this turbine was not determined. The possible existence of such a transition angle should be noted, however, and extrapolation beyond the values of the inlet angles shown is not recommended.

In order to demonstrate more effectively the difference in slope of the correlation curves, figure 3(b) shows a comparison of the least-square curve through the data for the 37° gas-flow inlet angle and a curve through the data obtained at the computed 49° gas-flow inlet angle. The slope of the 49° curve is considerably less. Such a a difference in slope may be accounted for by separation of the gas flow from the blade surface, which, in turn, affects the gas-to-blade heat transfer. Considerable separation is likely to occur when the turbine is operated at an inlet angle that is very much in excess of the design gas-flow inlet angle.

Comparison of rotating and static-cascade data. - A comparison of the least-square curve through the aluminum-turbine data obtained at the computed gas-flow inlet angle of 37° with results obtained in two static-cascade investigations is shown in figure 4. Comparison is made with the NACA heated impulse-blade data and the British impulse-blade data. The difference in blade contour can be seen in figure 4. Comparison, however, is made with these static-cascade investigations because, of all the data available, these blades most nearly approximated the aluminum-turbine impulse blade. The NACA heated impulse-blade data and the British impulse-blade data are recalculated in reference 5 and correlated with the density and the fluid properties of the gas based on average blade-wall temperature. The curve representing the aluminum-turbine data agrees within 9 percent with the static-cascade investigations and covers approximately a 35-percent-greater range of Reynolds numbers than in a similar comparison shown in reference 6. Because of the continued agreement between these curves over an extended Reynolds number range, static-cascade data can apparently be applied to this turbine. The slight difference in slope can probably be accounted for by the differences in the blade geometry, which affect the gas flow in the boundary layer and, consequently, the convection heat-transfer coefficient. Also, the successful application of static-cascade data to other rotating turbines with similar blade shapes appears more probable although the three-dimensional flow condition that occurs in turbines cannot be duplicated in a static cascade.

Comparison of experimental and computed convection coefficients. - A comparison of the least-square curve through the aluminum-turbine data obtained at the gas-flow inlet angle of 37° with a gas-to-blade heat-transfer correlation computed by boundary-layer theory for the aluminum turbine blade is presented in figure 5. The computed correlation curve agrees within 3 percent with the curve representing the experimental data.

The agreement achieved in the comparison of the computed gas-to-blade heat-transfer correlation and the correlation obtained from data for the aluminum turbine is comparable to the good agreement obtained between computed and experimental results from static cascades shown in reference 7. Thus, additional evidence of the validity of the theoretical method is provided. An average coefficient to the blade, the blade tip, and the disk rim is obtained from the aluminum-turbine data, whereas the theory of reference 7 deals with a coefficient about the blade periphery.

Use of a stream-filament theory to obtain the blade velocity distribution, which is subsequently employed in the theoretical method for computing gas-to-blade heat transfer, however, may introduce inaccuracies with an impulse blade, as previously mentioned herein.

In order to determine the effect of variations in the velocity distribution on the computed heat-transfer results of this investigation, another velocity distribution, 20 percent higher than that calculated by stream-filament theory, was assumed around the aluminum turbine blade. Recalculation of the convection gas-to-blade heat-transfer correlation by the method of reference 7 resulted in a correlation curve displaced somewhat from its present position, but agreeing within 15 percent with the experimental data.

From the agreement between the predicted and experimental gas-to-blade heat-transfer results, boundary-layer theory may be used for this turbine configuration at the design gas-flow inlet angle to predict the gas-to-blade convection heat-transfer correlation.

SUMMARY OF RESULTS

The following results were obtained from the investigation of gas-to-blade heat transfer conducted on a forced-convection, water-cooled aluminum turbine:

1. Average gas-to-blade convection heat-transfer coefficients were correlated by the general relation that expresses Nusselt number as a function of Reynolds and Prandtl numbers. Radiation to the blades was negligible. The root-mean-square deviation of the data obtained at the nominal-design gas-flow inlet angle of 37° was $5\frac{1}{2}$ percent.

2. Individual correlation curves were obtained for the Reynolds number range covered at gas-flow inlet angles of 25°, 37°, 43°, and 49°. An average increase of 34 percent in the heat-transfer rate resulted for the 18° increase in inlet angle from 25° to 43°.

3. The gas-to-blade heat-transfer correlation obtained at the 37° gas-flow inlet angle agreed within 9 percent with the results from two static-cascade investigations.

4. The results indicated that boundary-layer theory may safely be used for this turbine configuration at the design gas-flow inlet angle to predict a gas-to-blade convection heat-transfer coefficient.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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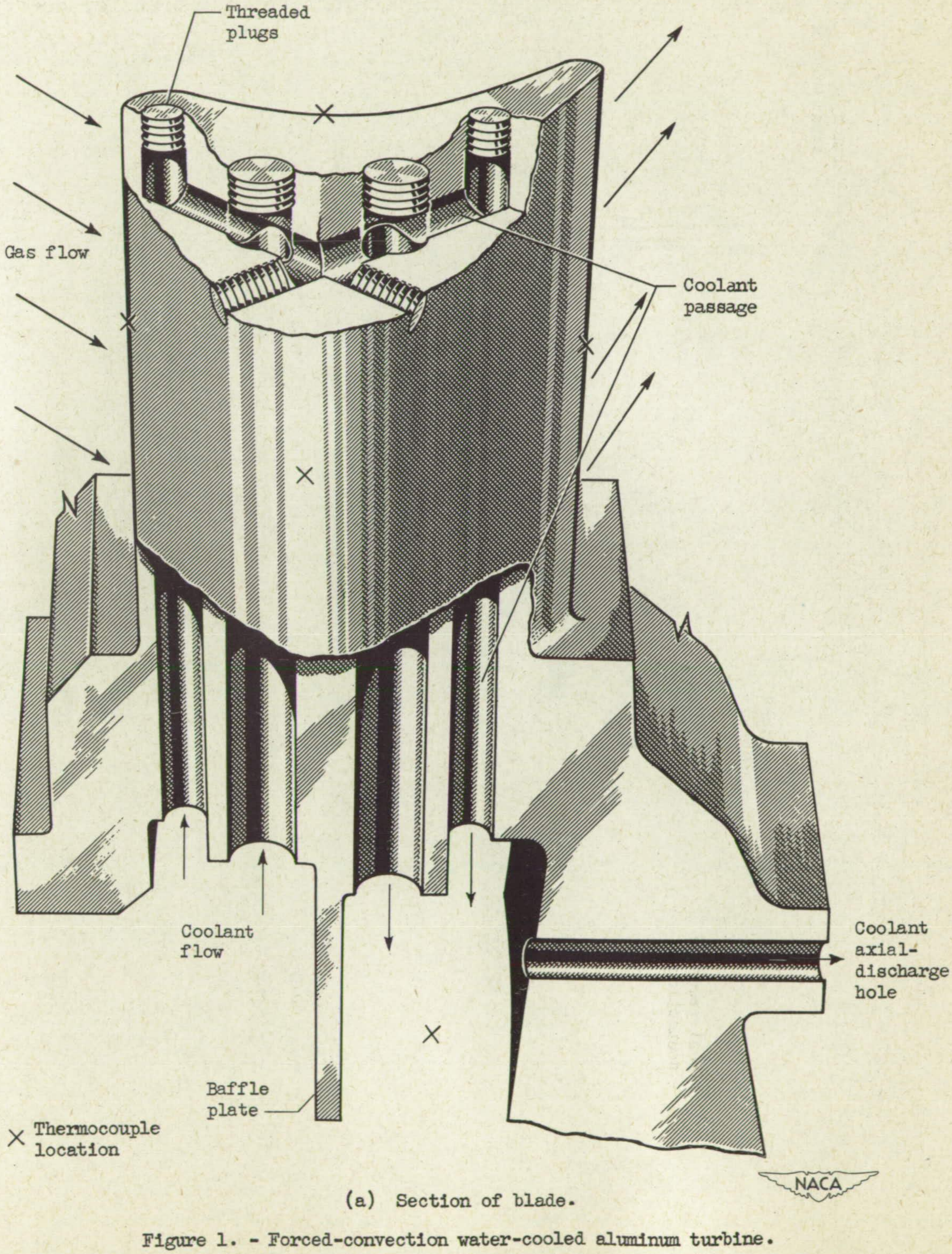
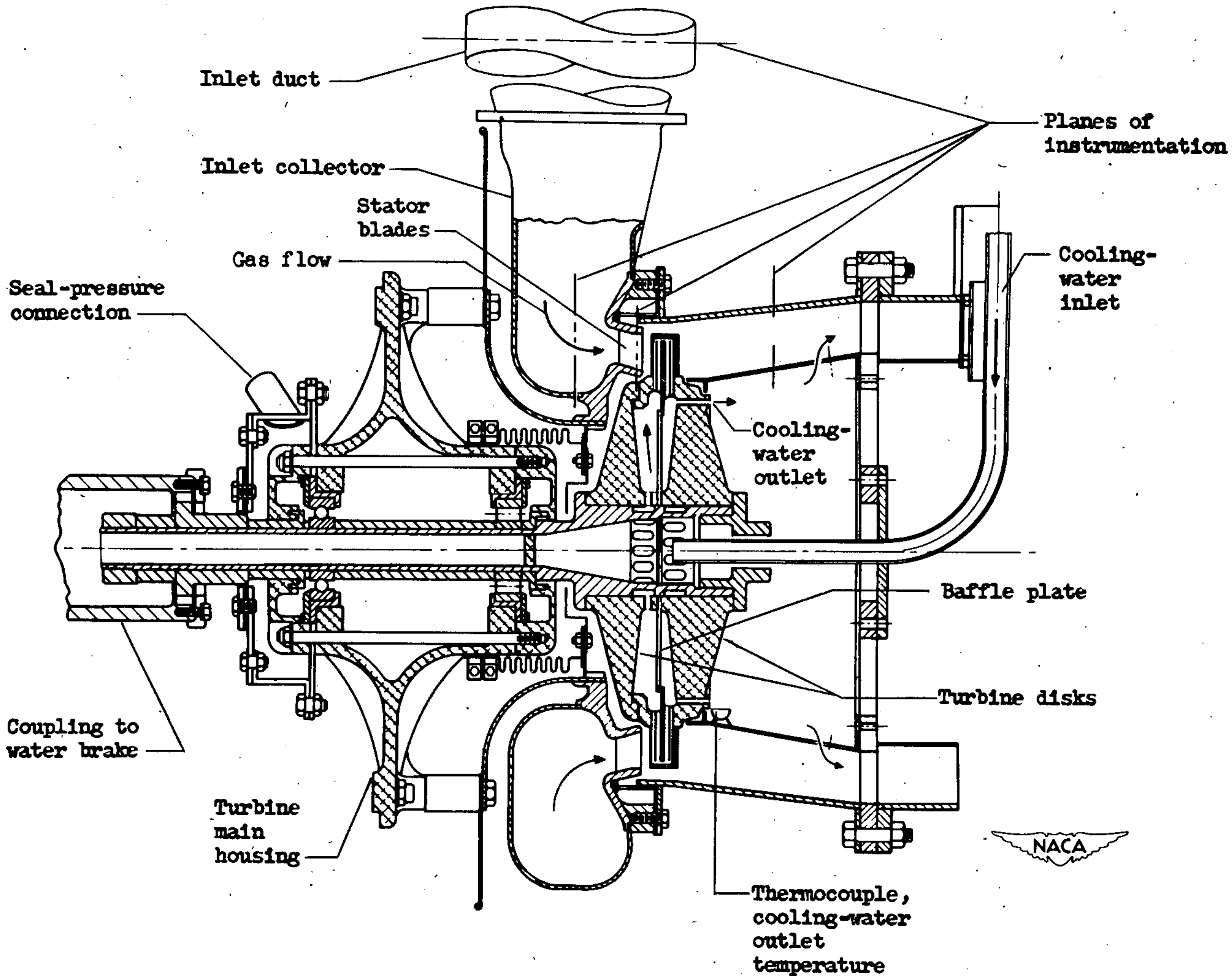
TABLE I - RANGE OF OPERATING CONDITIONS FOR VARIOUS GAS-FLOW INLET ANGLES

Gas-flow inlet angle (deg)	Turbine inlet-gas temperature (°F)	Total-to-static pressure ratio at nozzle throat	Turbine speed (rpm)	Inlet pressure (in. Hg abs)
25	400	1.08-1.6	1000-3000	22-38
37	250-1250	1.1-1.6	3400-13,500	21-38
43	400	1.1-1.5	5800-12,000	23-38
49	400	1.05-1.4	4700-12,000	21-33



(a) Section of blade.

Figure 1. - Forced-convection water-cooled aluminum turbine.



(b) Cross section of installation.

Figure 1. - Concluded. Forced-convection water-cooled aluminum turbine.

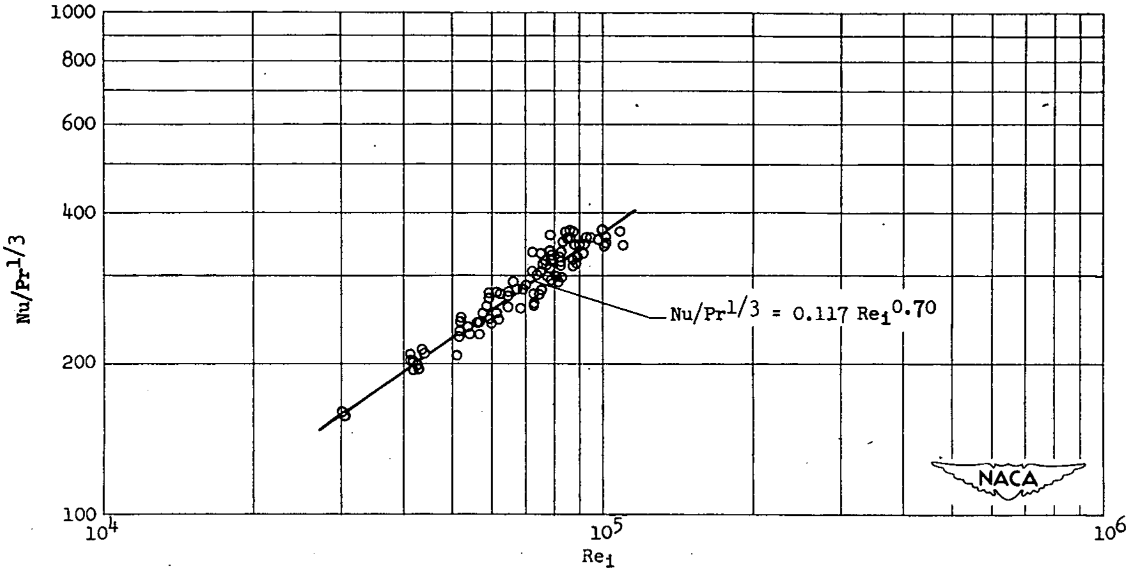
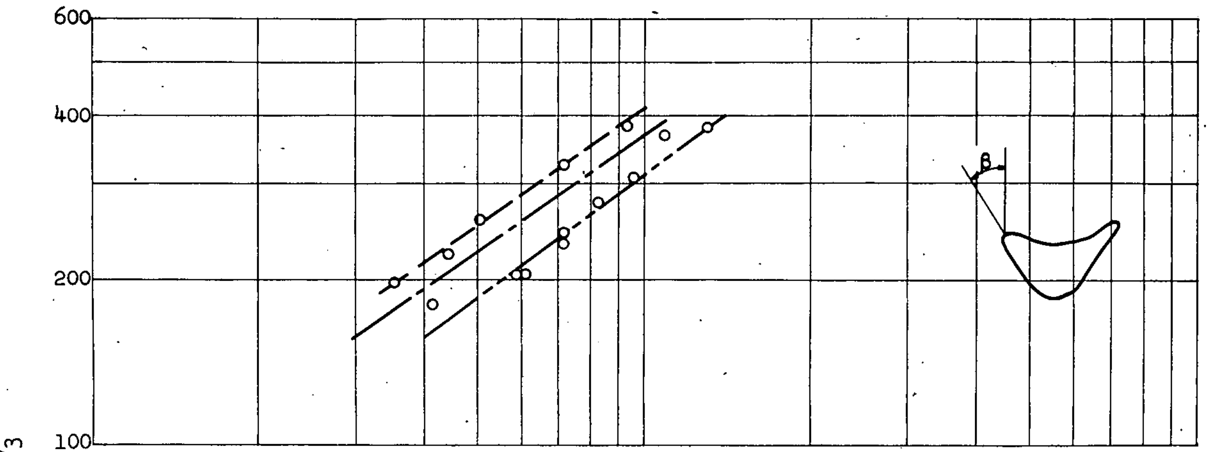
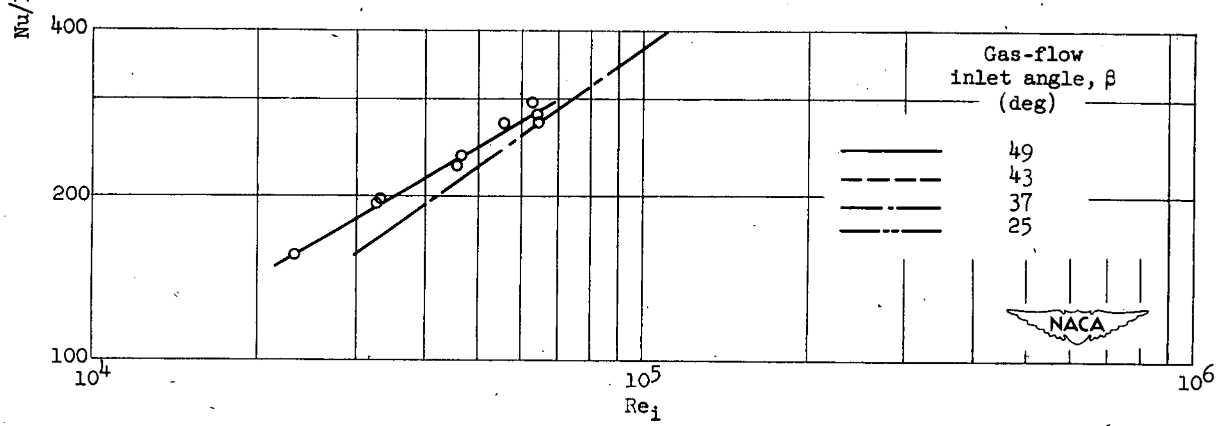


Figure 2. - Gas-to-blade heat-transfer data from forced-convection, water-cooled aluminum turbine for computed design gas-flow inlet angle of 37°. Density of gas based on static pressure at rotor inlet and average blade temperature; fluid properties of gas based on average blade temperature; velocity taken at rotor inlet.



(a) Comparison of aluminum-turbine data at gas-flow inlet angles of 25°, 37°, and 43°.



(b) Comparison of aluminum-turbine data at gas-flow inlet angles of 37° and 49°.

Figure 3. - Gas-to-blade heat-transfer data from aluminum turbine for computed gas-flow inlet angles of 25°, 43°, and 49° compared with least-square curve through experimental data for design gas-flow inlet angle of 37°. Density of gas based on static pressure at rotor inlet and average blade temperature; fluid properties of gas based on average blade temperature; velocity taken at rotor inlet.

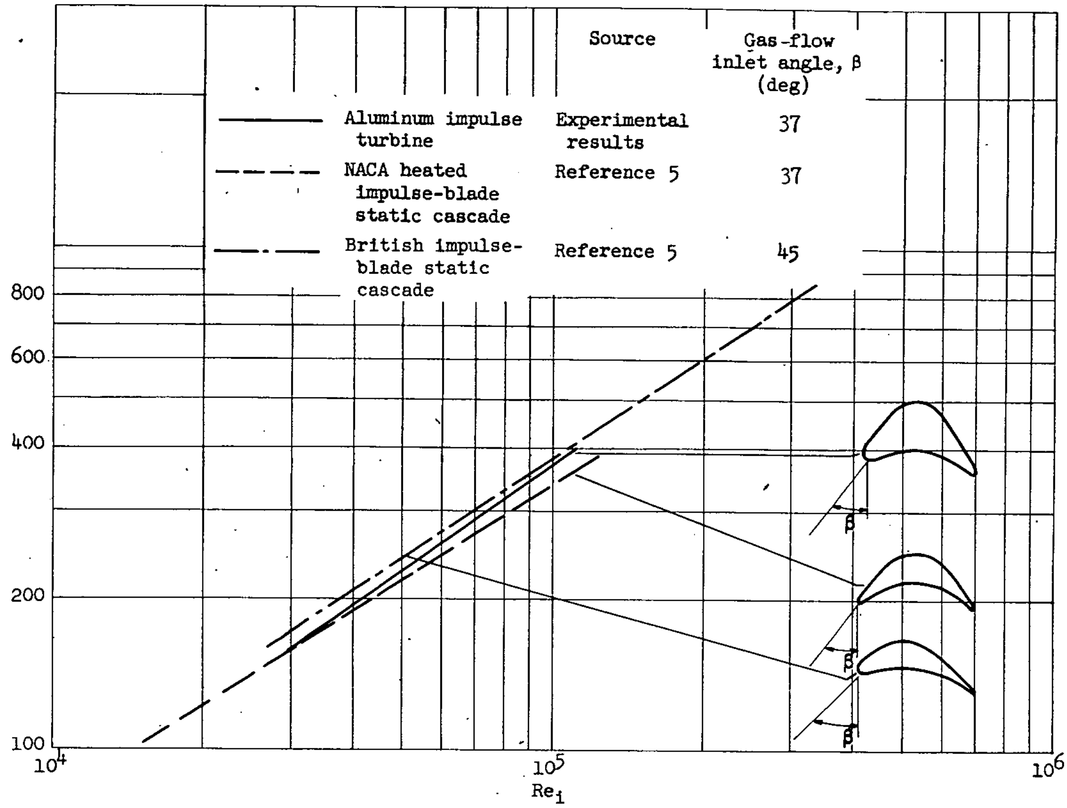


Figure 4. - Comparison of least-square curve through gas-to-blade heat-transfer data of aluminum turbine for computed design gas-flow inlet angle of 37° with results from static cascades (reference 5). Density of gas based on static pressure at rotor inlet and average blade temperature; fluid properties of gas based on average blade temperature; velocity taken at rotor inlet.

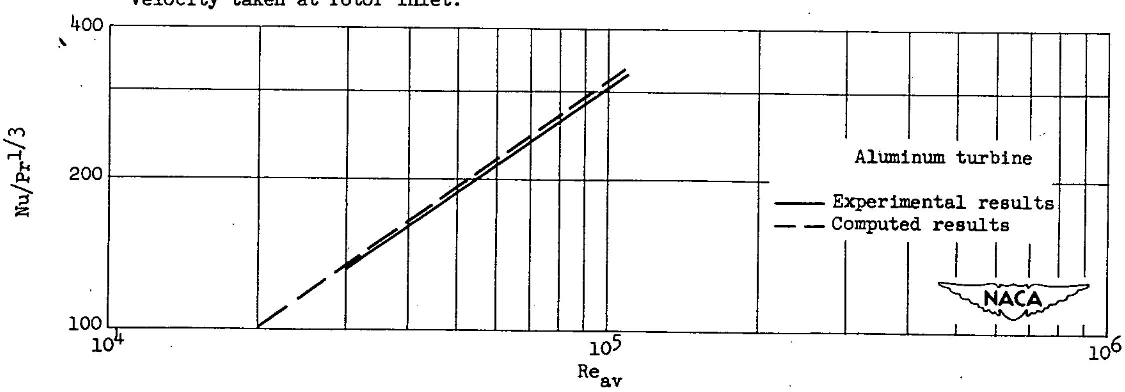


Figure 5. - Comparison of least-square curve through gas-to-blade heat-transfer data of aluminum turbine for computed design gas-flow inlet angle of 37° with correlation curve computed from boundary-layer theory. Density of gas based on average static pressure around blade and average blade temperature; fluid properties of gas based on average blade temperature; velocity taken as average around blade.

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